Diavik Waste Rock Project: From the Laboratory to the Canadian Arctic[1]

Lianna J.D.Smith[2,3], Matthew Neuner[4], Michael Gupton[4], Mandy Moore[3], Brenda Lee Bailey[3], David W. Blowes[3*], Leslie Smith[4] and David C. Sego[5]

[2] Rio Tinto (Diavik Diamond Mines Inc.), Yellowknife, Northwest Territories, Canada, X1A 2N8

[3] Dept. of Earth and Environmental Sciences, Univ. Waterloo, Waterloo, ON, Canada, N2L 3G1
*corresponding author: blowes@sciborg.uwaterloo.ca

[4]Dept. of Earth and Ocean Sciences, Univ. British Columbia, Vancouver, BC, Canada, V6T 1Z4

[5]Dept. of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada, T6G 2W2

ABSTRACT

The accuracy of using laboratory-scale experiments to predict drainage quality from mining waste rock piles is not well understood. A rigorous study to measure and compare waste rock and drainage characteristics at various scales has been designed, constructed and is being monitored at the Diavik diamond mine in the Northwest Territories, Canada. The objectives of the program are to characterize the physicochemical processes occurring in waste rock piles in a permafrost environment, and to quantitatively assess the application of small-scale laboratory experiments in the prediction of effluent quality from waste rock piles. Three well instrumented, large-scale waste rock piles were constructed from run of mine waste rock. Diavik waste rock has low sulfide content and has developed three rock classes for waste rock: Type I with a target of < 0.04 wt. % S, Type II with target 0.04 to 0.08 wt. % S and Type III with a target of > 0.08 wt. % S. A Type I pile, a Type III pile and a Type III pile with engineered dry covers were constructed. The piles are 15 m high with bases of at least 60 m by 60 m. Instruments and their distributions were selected to characterize coupled physicochemical processes at multiple scales and the evolution of those processes over time. Waste rock sampling during pile construction provided grain size distribution and sulfur content data. Initial field results are consistent with results from a series of complimentary laboratory experiments: effluent from the lower sulfide waste rock has higher pH, lower conductivity and lower dissolved metals compared to effluent from the higher sulfide waste rock; and temperature affects effluent quality.

ADDITIONAL KEY WORDS: ACID MINE DRAINAGE (AMD), SCALE-UP, PERMAFROST, SULFIDE OXIDATION, CHARACTERIZATION

---

[1] Paper presented at Securing the Future and 8th ICARD, June 23-26, 2009, Skellefteå, Sweden.

INTRODUCTION

Understanding physciochemical processes that result in acid mine drainage (AMD) generation and attenuation has serious environmental and economic implications for mining companies. Mining companies typically use laboratory-scale experiments to predict the acid-generating potential of mining wastes, and the associated environmental impacts of the AMD. The accuracy of using laboratory scale results for predicting field-scale behaviour is not well understood.

Predicting and evaluating AMD from low sulfide mining waste stockpiles is an emerging research area. A rigorous study to measure and compare waste rock and drainage characteristics at various scales has been designed and constructed, and is being monitored. The study consists of 36 column experiments, six field lysimeters at the 2 m scale and three 15 m high instrumented waste rock piles. The field experiments are located at the Diavik diamond mine in the Canadian Arctic. The objectives of the study are to: assess techniques that predict drainage quality of waste dumps from smaller-scale field and laboratory experiments, and; characterize flow, thermal and gas transport regimes, and geochemical and microbiological processes in low-sulfide waste rock in areas of continuous permafrost.

Location and Climate

3The Diavik diamond mine is located about 300 km northeast of Yellowknife in the Northwest Territories, Canada (Figure 1). The diamondiferous kimberlite ore bodies are located beneath the oligotrophic lake, Lac de Gras. A series of water-retention dikes have been constructed to permit open-pit mining, and all mine infrastructure, including waste rock stockpiles, are located on a large island within the lake.

The Diavik site is located in the treeless Arctic desert region of Canada, an area of continuous permafrost that receives little precipitation. The mean annual air temperature is -8.5 ºC with temperatures reaching 28 ºC in July and -47 ºC in February. Mean annual precipitation averages 280 mm, about 60% of which occurs as snow (Environment Canada, 2008).

Figure 1. Location of the Diavik Diamond Mine in the Canadian Arctic

Waste Rock Management

Open pit and underground mining of three diamondiferous kimberlite pipes at the Diavik site will expose about 200 Mt of low-sulfide waste rock to the environment by the end of mine life. Diavik country rock consists of granite and pegmatite granite that contains sulfide-bearing biotite schist xenoliths. Diavik waste rock management practices separate waste rock based on sulfur content. Type I waste rock is comprised of predominantly granitic rock with a target sulfur content of <0.04 wt%S. Type I waste rock is considered non-acid generating and is used for on-site construction material with minor amounts stockpiled. Type II waste rock has a target sulfur content of 0.04 to 0.08 wt%S and is stored in a dedicated Type II waste rock stockpile. Type III waste rock contains primarily granite with some amount of biotite schist and has a target sulfur content >0.08 wt%S. Because of the sulfide-bearing biotite schist component, Type III waste rock is considered potentially acid generating and is stockpiled in a dedicated storage area.

The current closure plan for Type III material proposes engineered dry covers. The Type III material would be contoured to a 3H:1V slope, capped by a 1.5 m till layer (derived from lakebed sediments stockpiled during initial pit development), followed by a 3 m "clean rock" Type I cover. The concept for the dry covers is based on the till remaining frozen and forming a low permeability layer, and the Type I cover acting as the thermal layer, in which seasonal freezing and thawing occurs. Permafrost is expected to form in the Type III core.

LABORATORY SCALE EXPERIMENTS

Laboratory scale experiments consist of standardized static and kinetic testing of Type I, Type II and Type III Diavik waste rock. Static and kinetic tests were conducted on each waste rock type collected in both 2004 and 2005. Static testing and waste rock characterization included paste pH, total sulphur, sulphate sulphur, sulfide sulphur, neutralization potential (NP), total carbon, net acid generation (NAG), acid whole rock analysis, grain size distribution (ASTM, 2002) and mean surface area. Acid base accounting (ABA) was conducted using the Sobek technique (Sobek et al., 1978).

Kinetic testing consists of 36 humidity cells each containing about 1 kg of waste rock. Half of the cells are being tested at 22ºC and the other half at 4ºC. At each temperature, tests include two cells of each Type I, Type II and Type III waste rock collected in 2004, and four cells of each waste rock type collected in 2005. Kinetic testing was initiated in 2005 and leachate continues to be analyzed for pH, Eh, electrical conductivity (EC), alkalinity, anions, cations and nutrients.

Of the cells containing 2005 waste rock, two cells at each temperature were inoculated with a bacterial consortium including *Acidithiobacillus ferrooxidans*. Bacterial population types were determined using the techniques described by Benner et al. (2000), and enumerations of acidophilic iron oxidizing bacteria (aIOB), acidophilic sulfur oxidizing bacteria (aSOB), and neutrophilic sulfur oxidizing bacteria (nSOB) were conducted using the most probable number (MPN) technique (Cochran, 1950).

FIELD SCALE EXPERIMENTS

2 m Scale Experiments

Six lysimeters, each 2 m by 2 m in diameter, comprise the 2 m scale field experiment. Two lysimeters were filled with and surrounded by Type I rock, and two lysimeters were filled with and surrounded by Type III rock. The other two lysimeters were filled with and surrounded by Type III rock, and capped with a 1.5 m thick till layer and a 3 m thick Type I cover. The Type I and Type III lysimeters were installed to measure the flow and geochemistry in the active zone of each rock type, whereas the covered lysimeters were installed to measure flow and geochemistry below the engineered dry covers to evaluate cover performance.

The Type I and Type III lysimeters continuously drain to a heated instrumentation trailer via a graded and heat-traced drain line housed in an insulated pipe. Drainage from these lysimeters is directed to a series of flow-through cells which allow for periodic geochemical sampling, and continuous measurements of pH and EC measurements. A tipping bucket flow gauge records flow volumes. In addition, a profile of moisture content sensors and tensiometers were installed in the Type III area to a depth of 0.9 m. The covered lysimeters have stand-pipes for periodic water level measurements and geochemical sampling.

15 m Scale Experiments

Three well instrumented waste rock piles (“test piles”) were constructed between 2005 and 2007. One pile is constructed from Type I run of mine rock; the second pile is constructed from Type III rock; and the third pile, referred to as the “covered pile” is constructed from Type III rock with slopes that were contoured to a 3H:1V slope and covered with 1.5 m till layer and a 3 m Type I cover. The Type I pile is designed to provide baseline information, the Type III pile is considered a “worst-case scenario”, and the covered pile will provide information about the proposed closure plan.

The height of the test piles were determined by preliminary thermal modelling using the reactive transport code SULFIDOX (Brown et al., 1999; Brown et al., 2001; Linklater et al., 2005). Based on simulations of gas and water transport, kinetically controlled sulfide oxidation, heat transfer, and ice formation in a Type III pile, a 15 m high pile ensured that thermal conditions at the top of the pile would not affect the stability of permafrost at the pile base. The dimensions of the pile bases were determined for a 20 m wide crest for a 15 m high pile. The Type I and Type III pile bases are 50 m by 60 m based on the angle of repose of waste rock (1.3H:1V); and the covered pile base is 80 m by 125 m, based on slopes contoured to 3H:1V, as per the current closure plan.

Past studies of waste rock piles have analysed data collected from instruments installed in vertical boreholes drilled post-construction, or from sampling points external to the waste dump (e.g. Harries and Ritchie, 1981, 1983; Lefebvre et al., 1993; Ericksson et al., 1997; Tan and Ritchie, 1997). Diavik test pile instrumentation planes were designed as angle-of-repose tip faces with the objective of assessing the influence of standard end-dumping and push-dumping construction methods on the thermal and physicochemical behaviour of waste rock dumps. The locations of angle-of-repose instrumentation planes within the piles were determined by SULFIDOX modelling. Four instrumentation planes located 5 m apart and 5 m from the final slope surface would capture potential oxygen gradients and seasonal fluctuations in the temperature regime that were evident in simulations with varied sulfide oxidation rates.

Instrument types and their distributions were designed to contribute to the characterization of coupled physicochemical process at multiple scales, the evolution of those processes over time, to provide sufficient redundancy in measurements and to ensure a sufficient number of instruments survived during pile construction.

Instruments at each pile base include thermistors, gas sampling lines, different-sized basal collection lysimeters and the basal drain. The basal drain systems and basal lysimeters drain to heated instrumentation trailers at the bases of the piles. All flow that reports to the basal drain and each lysimeter is directed through a series of flow-through cells and flow gauges. The flow-through cell configuration is the same as that described for the 2 m scale experiments, but the basal drain configuration also has a paddle-wheel flow gauge to broaden the range of possible flow measurements for times of increased basal drain flow. Face instrumentation includes time domain reflectometry (TDR) probes, soil water solution samplers (SWSS), gas sampling lines, air permeability probes, thermistors, access ports for thermal conductivity measurements, and access ports for microbiological characterization. General instrument distributions are illustrated in Figure 2.

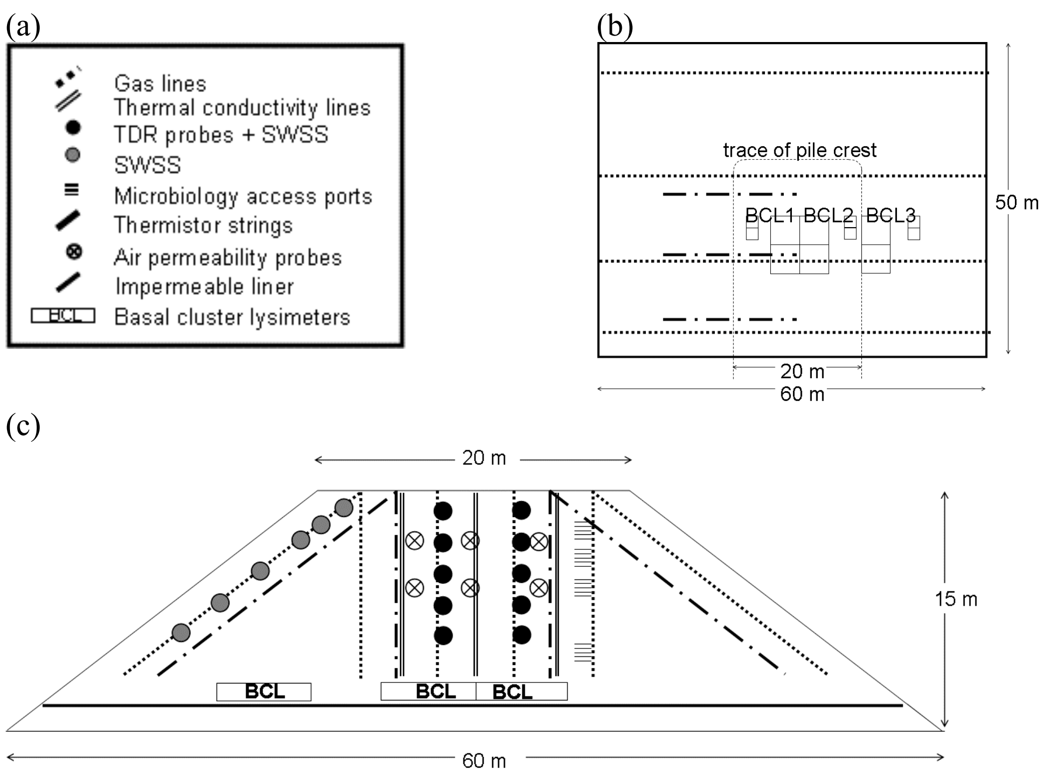

Figure 2. General instrumentation distribution (a) Legend; (b) Base instruments; (c) Face (in-pile) instruments.

Multiple scales of geochemistry and flow can be measured within the 15 m scale piles. SWSS and TDR probes within each pile provide point measurements of pore water solute loadings and matrix volumetric water content, respectively. The pore water geochemistry obtained from SWSS will be compared to the flux-averaged concentrations from different-sized basal lysimeters and the basal drain. Similarly, the velocity of the wetting front movement calculated using the volumentric water contents measured by TDR probes at various depths can be compared to the flow measured in each of the different-sized basal lysimeters and the basal drain. The two probe types are co-located to correlate matrix flow and pore water geochemistry within each pile.

Instruments were installed as the piles were being constructed. Standard mining equipment placed run of mine rock for the foundations of the piles. Crushed kimberlite or esker sand was placed on the foundations and graded to 0.5 to 1%. Thermistor strings were installed 10 m into bedrock in vertical boreholes beneath the piles and in horizontal trenches within the crushed kimberlite or sand. An impermeable high density polyethylene (HDPE) liner was placed on the graded foundation. Together with 6-inch perforated PVC pipe, the HDPE liner forms the basal drain collection system that conveys all infiltrating meteoric water to measurement points in the heated instrumentation trailers.

To protect the basal drain system during pile construction, a 0.3 m thick layer of crushed Type I rock was placed on the liner. This crushed rock also provided a platform for the basal collection lysimeter system, which consists of three clusters of lysimeters. Two clusters are located beneath the pile crests and one cluster is located beneath the pile slope. Each cluster consists of two 2 m by 2 m lysimters and two 4 m by 4 m lysimeters with walls at least 0.6 m high to prevent wicking effects. Each lysimeter is lined with HDPE, graded to drain to a dedicated drain line that directs water to an instrumentation trailer for geochemistry and flow measurements. The lysimeter boxes were filled with <0.5 m run of mine rock, consistent with each pile type (i.e. Type I material was used for the Type I pile and Type III material was used for the Type III pile and covered pile), to ensure compositional and textural consistency with the bulk pile material.

A 2 m thick layer of run of mine material (consistent with each pile type) was placed on the cover material for additional protection during pile construction. Gas sampling lines were installed within this layer to measure the gas composition at the base of the pile. Gas sampling lines consist of ¼-inch or smaller diameter low density polyethylene or nylon tubing strung through flexible PVC conduit with sample ports at 3 to 5 m intervals. The flexible PVC conduit was used to protect the sample lines from damage during construction.

Standard mining equipment was used to end-dump and push-dump run of mine material from a 15 m high access ramp onto and across the completed pile bases. At each instrumentation face, construction was stopped and instruments were installed along the angle of repose tip face. Instrument locations were surveyed using GPS. An excavator covered the face instrumentation lines with run of mine rock to a thickness of 0.5 to 1 m for protection before dumping from the access ramp resumed. At the top of the piles, instrument cables were protected by 1 to 2-inch thick HDPE covers and buried beneath

0.5 m of run of mine rock. After pile construction was complete, instrument leads were excavated and extended to the surface to permit installation of dataloggers and manual measurements, and tensiometers were installed in the upper 1.5 m of the Type III pile to monitor recharge.

The covered pile required additional construction and instrumentation. The angle of repose slopes were contoured to a 3H:1V slope. A 1.5 m thick layer of till was placed on the resloped core and the crest. The crest instrument cables were extended and reburied in the till layer. Additional thermistor lines, air permeability probes and gas sampling ports were installed in the till layer. A 3 m thick Type I cover was placed on the slopes and thermistors were installed in this cover. There was a delay in excavating and extending the crest instruments buried in till because of equipment availability. When equipment became available, the till had frozen and exposing the instrument lines required an excavator fitted with a chisel tip. Exposing and extending the instrument lines in winter conditions reduced the number of instrument lines that could be extended successfully: the difficulty in chiselling till caused some instrument lines to be abandoned or irrecoverably damaged during the excavation step; and the cold temperatures caused instrument tubing and protective conduit to become brittle, causing some instrument lines to crack or shatter during the extension step. After instrument lines were exposed, the 3 m Type I layer on the crest of the pile was completed and the instrumentation lines were prepared for datalogging and/or manual measurements.

Additional instruments were installed in boreholes in the covered pile. A total of ten boreholes were drilled: six vertical boreholes drilled on the slopes into the till layer; three vertical boreholes drilled on the crest; and one borehole at a 30º angle. ECH_2O probes, which measure moisture content and electrical conductivity, were installed within the till layer in the slope boreholes. Access ports for microbiology, access ports for thermal conductivity, ECH_2O probes, SWSS probes, gas sampling ports and thermistors were installed within the boreholes drilled from the crest. The boreholes were backfilled with Type I 1-inch minus crushed rock, or till for the till intervals.

Full Scale Experiment

Planning is underway to install instruments in one or more boreholes in the Type III waste rock dump in order to characterize the physicochemical processes occurring in the full-scale dump and to provide an additional scale for measurement comparison. The target location is above the low point of the ground beneath the dump, about 80 m beneath the existing top of the Type III dump. The borehole(s) will contain gas sampling lines, air permeability probes, thermistor strings, ECH_2O probes, SWSS, microbiology access ports and thermal conductivity access ports. The detailed design will be completed once drill rig availability and capabilities (e.g. borehole diameter) are finalized.

INITIAL CHARACTERIZATION

Grain size distribution and sulfur distribution

During construction, 2-5 kg samples of the < 50 mm fraction of waste rock were collected for sulfur analysis and 5-10 kg samples were collected for grain size analysis. Samples were collected from most haul truck loads delivered to the test piles. Additional samples were collected directly from the instrumentation faces.

Table 1 summarizes the sulfur content of each pile based on the < 50 mm fraction. Samples were collected, pulverized, homogenized, and analyzed on-site using a procedure consistent with standard Diavik waste rock management sulfur analysis. Results of the sulfur analyses for each pile show that the Type I pile average sulfur content is towards the high-end of the Diavik Type I classification, the Type III pile average sulfur content is below the Diavik Type III target sulfur content, and the Type III core of the covered pile is within the range for Diavik Type III classification. The covered pile core was built after the Type III pile. Run of mine rock delivered to build the test piles was classified by Diavik as part of Diavik waste rock management and is considered representative of waste rock moved to the Type I and Type III Diavik waste rock dumps during the same time periods as pile construction.

Table 1. Sulfur content summary for the Type I, Type III and Covered Pile (core only) test piles

	Average Wt%S	n
Type I Pile Average	0.035	242
Type III Pile Average	0.054	327
Covered Pile Core Average	0.082	183

Table 2 summarizes the grain size distribution of the <50 mm fraction of each of the piles. Grain size characterization of the finer fraction of the test piles material is important to flow and geochemical characterization. This grain size characterization permits an estimation of the bulk hydraulic conductivity, pile moisture content, and reactive surface area within the pile, but cannot provide information about spatial heterogeneity and preferential flow (Smith and Beckie, 2003).

Table 2. Grain size summary for Type I, Type III and Covered Pile (Type III core only) test piles. Approximately 5-10 kg hand samples of the <50 mm fraction were collected from loads delivered during pile construction.

	d10 (mm)	d30 (mm)	d50 (mm)	CU(d60/d10)	n
Type I Pile Average	0.23	2.16	7.96	57.75	66
Type III Pile Average	0.22	1.80	7.08	55.87	77
Covered Pile Core Average	0.23	2.90	10.13	79.27	27

Initial characterization of the hydraulic properties shows large variances in hydraulic conductivity (10^{-6} to 10^{-2} m/s), depending on sample characteristics, measurement scale and measurement technique. Similarly, a series of preliminary water retention curves based on Tempe cell tests using the < 5 mm fraction was derived for matrix material (Neuner et al., 2009).

The relationship between physical and geochemical properties, including preferential flow, will be characterized, refined and compared at various scales as the study progresses.

Initial Geochemical Response

Water samples were collected during the first field season (2007) from the Type III pile basal drains, SWSS, and 2 m scale lysimeters, the Covered Pile basal drain and SWSS, and the Type I SWSS. Type III material data indicate sulfide oxidation is occurring in the Type III material: results indicate decreasing pH and a concomitant increase in conductivity, SO_4^{2-} and some dissolved metals (e.g. Ni, Cd, Co, Fe, Mn, and Zn). Sulfide oxidation appears to decrease when ambient temperatures decrease (Figure 3); this potential trend will be evaluated further with additional data collected in subsequent field seasons.

Few samples were collected in 2007 from the Type I field material because the basal drain system was damaged and low moisture content within the test pile and 2 m scale experiments restricted water sampling. The limited 2007 Type I data set shows circum-neutral pH with occasional elevated sulphate levels. Additional data from subsequent field seasons is required to further analyse the trends in the Type I field material. Lab results for the Type I columns show circumneutral, fairly constant pH values and low concentrations of dissolved constituents including SO_4^{2-}, Ni, Cd, Co, Fe, Mn, and Zn.

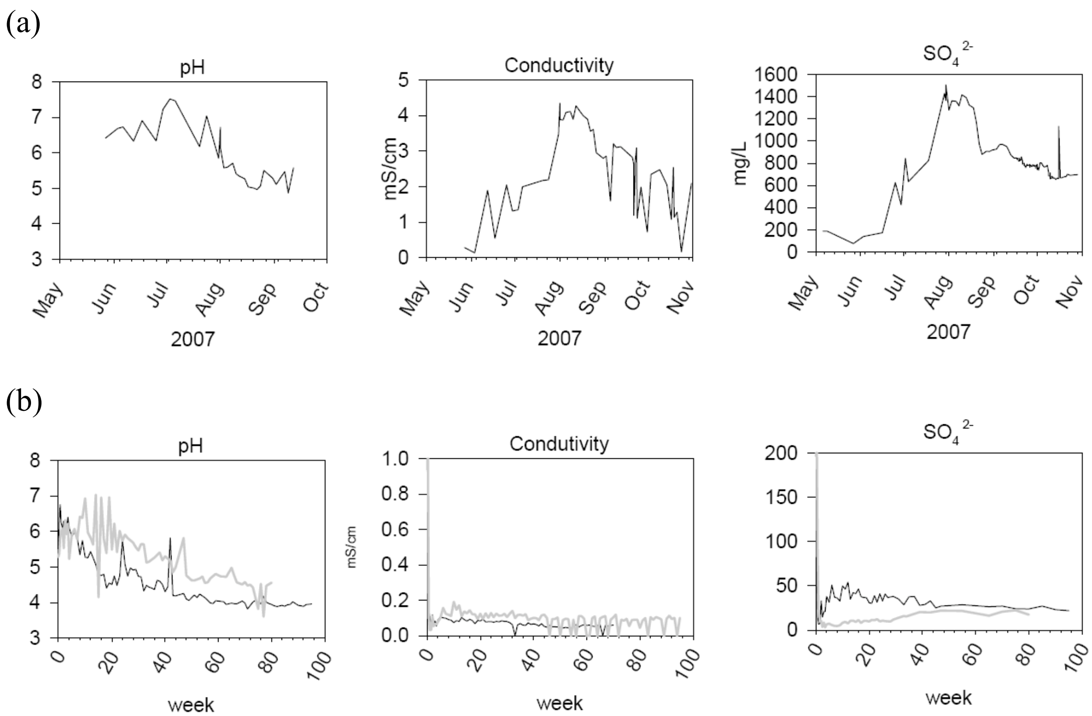

Figure 3. (a)Type III basal drain field results; and (b) Type III material lab results at room temperature (black line) and at 4ºC (grey line)

Initial field results are consistent with results from the laboratory experiments: the higher sulfide Type III material shows lower pH, higher conductivity, and higher dissolved metals concentrations compared to the lower sulfide Type I waste rock, and sulfide oxidation appears to decrease with decreasing ambient temperature.

CONCLUSIONS

On-going data collection in the lab and in the field will provide further refinements, characterization, and interpretation of the physicochemical processes and the relationship between those processes occurring at various scales in the lab and in waste dumps in the Canadian Arctic.

ACKNOWLEDGEMENTS

This research is made possible through funding provided by Rio Tinto (Diavik Diamond Mines Inc.), the Canada Foundation for Innovation, the Natural Science and Engineering Research Council of Canada, the International Network for Acid Prevention, and the Mine Environment Neutral Drainage program. We thank: J. Reinson, G. MacDonald, S. Wytrychowski and L. Clark of Diavik Diamond Mines Inc. for their support and commitment to the project; T. Deans, J. Tymstra, J. McKellar and E. McCulloch of FDA Engineering; and field assistants and technicians from the University of Waterloo, the University of Alberta and Environment Canada. Technical and field assistance from J. Bennett, A. Garvie and C. Linklater of the Australian Nuclear Science and Technology Organisation was greatly appreciated.

REFERENCES

ASTM D422-63 Standard Test Method, 2002. Standard test method for particle-size analysis of soils. In: Annual Book of ASTM Standards, American Society for Testing and Materials.

Benner, S.G., Gould, W.D., Blowes, D.W. 2000. Microbial populations associated with the generation and treatment of acid mine drainage. Chemical Geology 169, 435-448.

Brown, P., Luo, X-L., Mooney, J., Pantelis, G. 1999. The modelling of flow and chemical reactions in waste piles. p. 169-174. Second International Conference on CFD in Minerals and Process Industries. (Melbourne, Australia, December 6-8).

Brown, P.L., Crawford, J., Irranejad, P., Miskelly, P.C., Noël, M.M., Pantelis, G., Plontikoff, W.W., Sinclair, D.J., Stpanyants, Y.A. 2001. SULFIDOX: Version 1.1 A tool for modelling the temporal and spatial behaviour of heaps containing sulfidic minerals. ANSTO Techical Report, ANSTO/ED/TN01-03.

Cochran, W.G. 1950. Estimation of bacterial density by means of “Most Probable Number”. Biometrics, 6, 106-116.

Environment Canada. 2008. Monthly data report for Ekati A, Northwest Territories, Bulk Data1998-2007.Accessibleat: http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html.

Eriksson, N., Gupta, A., Destouni, G. 1997. Comparative analysis of laboratory and field tracer tests for investigating preferential flow and transport in mining waste rock. J. Hydrol. 194, 143-163.

Harries, J.R., Ritchie, A.I.M. 1981. The use of temperature profiles to estimate the pyritic oxidation rate in a waste rock dump from an opencut mine. Water Air Soil Pollut. 15, 305-423.

Lefebvre, R., Gélinas, P., Isabel, D. 1993. Heat transfer during acid mine drainage production in a waste rock dump, La Mine Doyon (Québec). MEND report 1.14.2c, March 1994, 106 pp.

Linklater, C.M., Sinclair, D.J., Brown, P.L. 2005. Coupled chemistry and transport modelling of sulfidic waste rock dumps at the Aitik mine site, Sweden. Appl. Geochem. 20, 275-293.

Neuner, M., Gupton, M., Smith, L., Smith, L., Blowes, D.W., Sego, D.C., 2009. Diavik Waste Rock Project: Unsaturated Water Flow. Presented at the 2009, Securing the Future and 8th ICARD, June 22-26, 2009, Skellefteå, Sweden.

Smith, L. and R. Beckie. 2003. Hydrologic and geochemical transport processes in mine waste rock. p. 51-72. In Jambor, J.L., D.W. Blowes and A.I.M. Ritchie (eds). Environmental Aspects of Mine Wastes, Mineral. Assoc. Can. Short Course, 31.

Sobek, A.A., Schuller, W.A., Freeman, J.R., Smith, R.M. 19789. Field and laboratory methods applicable to overburdens and minesoils. EPA report no. EPA-600/2-78-054.

Tan, Y. and Ritchie, A.I.M. 1997. In situ determination of thermal conductivity of waste rock dump material. Water, Air and Soil Pollut. 98, 345-359.